CIRCUMFERENTIAL MEASUREMENT OF TUBULAR MEMBERS

BACKGROUND OF THE INVENTION

1) Field of the Invention

The present invention relates to apparatuses and methods for measuring a tubular member and, more specifically, for measuring one or more cross-sectional characteristics of the tubular member.

2) Description of Related Art

Tubular members such as pipes, ducts, and the like are used in various applications, for example, as transport passageways through which gases can be delivered for heating, ventilation, and air conditioning. In other applications, pipes, ducts, and other tubular members can also be used to deliver liquids, such as water, waste liquids, and the like. In the aircraft industry, tubular members are provided as ducts in environmental control systems (ECS) of modern commercial aircraft. An ECS and, hence, the ducts therein, provides air throughout the cabin of the aircraft in order to provide air as required for the respiratory needs of the occupants, to clear contaminants and odors from the cabin air, to control the temperature and humidity of the cabin environment, and to provide adequate cabin pressure. Air can also be delivered throughout the aircraft for de-icing of the aircraft, for heating of the cargo area of the aircraft, for pneumatic systems, and for cooling hydraulic and electrical systems.

The tubular members used for ducts, such as for the ECS of an aircraft, are typically formed of composite or metallic materials. Common composite reinforcement materials include fiberglass (BMS 8-80, 8-139, or 8-226), graphite (BMS 8-168), and Kevlar® (BMS 8-264), a registered trademark of E.I. du Pont de Nemours and Company. These reinforcement materials, which can be provided as sheets, fibers, or the like, can be preimpregnated with epoxy or polyester resin, which hardens when subjected to heat and pressure. Alternatively, the reinforcement materials can be reinforced with thermoplastic materials such as polyetherimide

(PEI), which is available under the trade name Ultem®, a registered trademark of General Electric Company. In either case, ducts formed of composite materials can be lightweight and strong. Alternatively, the tubular members can be relatively thin-walled structures that are formed of metals such as steel.

Tubular members, such as composite ducts, are typically dimensionally tested, e.g., by measuring the circumference or diameter of the member to see if the cross-sectional size of the member matches the desired size. For example, the inner or outer diameter of the tubular member can be measured using a gauge, calipers, micrometers, and the like. However, due to the flexible nature of composite materials and many thin-walled structures, the tubular members can flex during testing, thereby reducing the accuracy of the measurement. Alternatively, the tubular member can be measured by extending a flexible measuring tape around the circumference of the member. In the case of a "pi tape," the measurement units marked on the tape are adjusted by the value of the pi constant, i.e., the marked units reflect the linear length of the tape divided by pi. Thus, an operator can quickly determine the diameter of the tubular member by extending the tape around the tubular member and reading the diameter from the circumferential markings on the tape. However, regardless of the units provided on the measuring tape, the measurement made therewith is dependent on the placement of the tape and the reading that is taken by the operator. Thus, like the other mechanical measuring devices listed above, the accuracy of the tape is limited by the ability of the operator.

In yet another conventional method of measurement, an electronic coordinate measuring machine is used to determine relative coordinate positions for several points around the circumferential perimeter of the tubular member. The coordinate positions are then used to determine the cross-sectional size of the member, e.g., by using a "best-fit" technique in which the coordinate positions are matched up with an equation describing a best-fit circle, and a circumference of the member is thereby approximated. The coordinate measuring machine can be capable of very accurately determining the positions of the several points, but the circumference determined by the machine is only an approximate measurement. In particular, if the cross-sectional shape of the member is not circular, the best-fit circle will not accurately correspond to the cross-sectional shape of the member, and the accuracy of the dimensions determined with the machine can be decreased.

Thus, there exists a need for an apparatus and method for accurately measuring the cross-sectional characteristics of a tubular member formed of a thin-walled or otherwise flexible material. The apparatus should be capable of accurately determining at least one characteristic, such as the diameter or wall thickness, of the tubular member, even if the cross-sectional shape of the member does not define a perfect or uniform polygonal shape such as a circle.

SUMMARY OF THE INVENTION

The present invention provides an apparatus and method for accurately measuring the cross-sectional characteristics of a tubular member. The apparatus includes cooperable template members that define an adjustable aperture for receiving the tubular duct. A measurement device detects the adjustment of the members and thereby measures one or more characteristics of the tubular member such as the diameter. The apparatus can urge the tubular member to a reference shape, e.g., if the tubular member in an unconstrained configuration defines an irregular or nonuniform cross-sectional shape. Further, the measurement can be performed accurately with a reduced dependence on the technique of an operator.

According to one embodiment of the present invention, the apparatus includes first and second cooperable template members, which cooperably define the aperture having a cross-sectional reference shape of the tubular member, e.g., a circle. Each of the first and second template members can include two or more plates configured in a spaced relationship. The first and second template members can be connected by a hinge connection and thus rotatably adjustable between open and closed positions. An urging device is configured to apply a predetermined force to the members to urge the members toward the closed position. The measurement device is configured to detect the relative position of the first and second template members, e.g., by measuring a gap between the first and second template members opposite the aperture from the hinge connection. Thus, the measurement device, which can be an electronic device configured to automatically measure the relative position of the template members, measures the relative adjustment of the members between the open and closed positions. The measurement device can also be configured to determine a diameter of the tubular member.

The present invention also provides a method for circumferentially measuring a tubular member. The method includes inserting the tubular member into an aperture defined by the first and second cooperable template members, and adjusting at least one of the template members to at least partially close the aperture, for example, by rotating one of the template members about a hinge connection between the template members. The tubular member is urged, e.g., by applying a predetermined force, to a cross-sectional shape corresponding to the reference shape of the aperture such as a generally circular cross-sectional shape. The relative position of the first and second template members is measured, and a cross-sectional size, such as a diameter, of the tubular member is determined according to the relative position of the first and second template members. The position of the template members can be measured by measuring a gap therebetween, e.g., at a position opposite the aperture from the hinge connection. An electronic measurement device can be configured to measure the relative position of the template members.

Further, the present invention provides an apparatus and method for measuring the tubular member at a plurality of circumferentially spaced locations. For example, measurement devices can be configured to contact the tubular member at the circumferential locations when the aperture is closed so that each measurement device provides an output that is characteristic of a contact force between the measurement device and the tubular member. The measurement devices can be configured to detect a force, pressure, or a stress that is representative of the stiffness of the tubular member. Thus, the variation of the wall thickness of the tubular member can be determined accordingly.

BRIEF DESCRIPTION OF THE DRAWINGS

Having thus described the invention in general terms, reference will now be made to the accompanying drawings, which are not necessarily drawn to scale, and wherein:

Figure 1 is a perspective view of an apparatus for circumferentially measuring a tubular duct according to one embodiment of the present invention;

Figure 2 is a top view of the apparatus of Figure 1, shown in an open configuration;

Figure 3 is a perspective view of a tubular duct that can be measured with the apparatus of Figure 1;

Figure 4 is an elevation view of the apparatus of Figure 1, shown in a closed positioned with the tubular member configured therein for measuring;

Figure 5 is an elevation view of an apparatus for measuring a tubular duct according to another embodiment of the present invention;

Figure 5A is an enlarged partially cutaway view of a portion of the apparatus of Figure 5 illustrating two of the measurement devices thereof;

Figure 6 is a partial section view of the apparatus of Figure 5, as seen along line 6-6 of Figure 5A;

Figure 7 is a partial elevation view of the apparatus of Figure 5, shown in a closed position with the tubular member configured therein for measuring;

Figure 8 is a graph illustrating the magnitudes of the outputs provided by the measurement devices of the apparatus of Figure 5;

Figure 9 is a graph illustrating the thickness of the wall of the tubular member at various circumferential locations as measured at a particular longitudinal position using the apparatus of Figure 5; and

Figure 10 is a graph illustrating the eccentricity of the tubular member as measured at various longitudinal positions using the apparatus of Figure 5.

DETAILED DESCRIPTION OF THE INVENTION

The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout.

Referring now to Figure 1, there is shown an apparatus **10** for measuring a tubular member **14** (Figure 3) according to one embodiment of the present invention. The apparatus **10** can be used for measuring a variety of tubular members **14**, such as pipes, ducts, tubes, and the like, which can be formed of metal, plastic, thermoplastic or thermoset composite materials, and other materials. Advantageously, the tubular

members **14** can be flexible, such as thin-walled metal members or tubular members **14** formed of flexible polymeric or composite materials. Such tubular members **14** can be used for duct passages in heating, ventilation, and air conditioning systems in aircraft, buildings, and the like. Additionally, the tubular members **14** can be used in a variety of other applications, for example, as flexible pipes for transporting other fluids such as for transporting steam, irrigation, drainage, or delivery of gas, oil, and the like. Further, the tubular members **14** can be used as structural members in building construction, for sports or medical devices, and the like.

The apparatus **10** is configured to circumferentially measure the tubular member **14** to determine one or more cross-sectional characteristics of the tubular member **14**. For example, the apparatus **10** can be configured to support the tubular member **14** about a circumference of the tubular member **14** and determine a diameter of the tubular member **14**. The diameter or other measurements of the tubular member **14** can be determined at various positions along the length of the member **14**, e.g., at each of the longitudinal positions $\mathbf{D_1}$-$\mathbf{D_8}$ shown in Figure 3. While the apparatus **10** shown in Figure 1 is structured to measure a tubular member **14** having a generally circular cross section, it is appreciated that the apparatus **10** in other embodiments can be used to measure tubular members **14** having other cross-sectional shapes including elliptical or oval shapes, rectangular shapes, contoured shapes, or nonuniform shapes.

As illustrated in Figure 1, the apparatus **10** includes first and second template members **20, 30** that cooperably define an aperture **40** extending therethrough for receiving the tubular member **14**. The first template member **20**, which is connected to a base **12**, includes a support member **22** and two plates **24, 26** that are connected to opposite sides of the support member **22**. Similarly, the second template member **30** includes a support member **32** and plates **34, 36** connected to opposite sides thereof. The plates **24, 26, 34, 36** can be connected by bolts **18** to the respective support members **22, 32** such that the plates **24, 26, 34, 36** can be removed for maintenance, repair, or replacement, e.g., with plates of different configurations to define different sizes or shapes of aperture **40**. In other embodiments of the present invention, each template member **20, 30** can be formed of multiple additional members, or each template member **20, 30** can be a unitary structure (that is, a

template member need not have two separate plates, but may have a single plate or other structure that defines a portion of the aperture).

The first and second plates **24, 26, 34, 36** of each template member **20, 30** can be generally similar in configuration. That is, the first and second plates **24, 26** of the first template member **20** can define a similar arcuate portion of the aperture **40** so that the first template member **20** corresponds to a portion of the curved cross section of the tubular member **14**. Similarly, the first and second plates **34, 36** of the second template member **30** can define a similar arcuate portion of the aperture **40** so that the second template member **30** corresponds to the remaining cross section of the tubular member **14**. Thus, the first and second template members **20, 30** cooperably define the aperture **40**, which corresponds to a reference or nominal cross-sectional shape of the tubular member **14**. Alternatively, the first and second plates **24, 26** of the first template member **20** can be define dissimilar portions of the aperture **40**, and the first and second plates **34, 36** of the second template member **30** can be correspondingly dissimilar so that the two template members **20, 30** in combination define the aperture **40**.

Thus, with the template members **20, 30** configured as shown in Figure 1, the aperture **40** extends through the apparatus **10**. The aperture **40** can be perpendicular to the plates **24, 26, 34, 36**, as shown, or the aperture can be disposed at an angle thereto. Also, the plates **24, 26, 34, 36** can define surfaces **25, 27, 35, 37** at the aperture **40**, which can be smooth cylindrical surfaces, as shown, or can define a V-shape or other grooves, ridges, or contours. At least one of the first and second template members **20, 30** is preferably adjustable so that the aperture **40** can be opened and closed. For example, the first and second template members **20, 30** can be connected at one end by a hinge **42** so that the second template member **30** can be rotated between an open position (Figure 2) and a closed position (Figures 1 and 4). In other embodiments, the template members **20, 30** can be otherwise adjustably connected, e.g., by rails or posts that extend from one of the members **20, 30** and are slidably received and supported by the other member **20, 30**. In the open position, the aperture **40** is open to more easily receive the tubular member **14**. The second template member **30** can be adjusted manually, e.g., using a handle **38** provided thereon. Alternatively, in other embodiments of the invention, an actuator, spring, or the like can be provided to achieve or facilitate the relative adjustment of the template

members **20, 30**. The template members **20, 30** are preferably formed of stiff materials such as aluminum or other metals. Holes **39** can be formed in one or both of the template members **20, 30** to reduce the weight of the members **20, 30** and reduce the energy required for adjustment.

A measurement device **50** is configured to detect the relative position of the first and second template members **20, 30**. For example, the measurement device **50** can be a conventional electronic position detection device such as a gauge that includes an adjustably extendable probe **52** that is biased by a spring to an extended configuration. The probe **52** is extendable from a probe housing **54** that is mounted on the first template member **20**, and a flange **56** on the second member **30** is structured to contact the probe **52** when the second template member **30** is closed relative to the first structural member **20**. Thus, the probe **52** is configured to be extended by the spring from the probe housing **54** when the second member **30** is adjusted toward the open position and retracted into the probe housing **54** as the second template member **30** is adjusted toward the closed position. A digital monitoring device **58** electrically communicates with the probe **52** and is configured to detect the extension or retraction of the probe **52** and thereby measure the relative position of the two template members **20, 30**. Other measurement devices can alternatively be used including, e.g., mechanical gauges, linear measuring references, optical measuring devices, and the like.

One or more shock absorption devices **60** can also be provided to reduce the shock on the measurement device **50** during closing of the template members **20, 30**. For example, each shock absorption device **60** can include a spring and a damper that are connected to the first template member **20** and configured to be acted on by the flange **56** or another portion of the second template member **30** when the second template member **30** is closed.

The first and second templates **20, 30** can be urged toward the closed position with a predetermined force provided by an urging device **62**. The predetermined force can be sufficient to urge a portion of the tubular member **14** to the reference cross-sectional shape defined by the aperture **40**. For example, the urging device **62** can be a weight that is placed on the second template member **30** as shown in Figure 1 to urge the second template member **30** toward the first template member **20**, thereby closing the template members **20, 30**. The weight **62** is preferably provided at a

predetermined position, i.e., so that a uniform force between the first and second template members **20, 30** can be provided during each subsequent operation of the apparatus **10**. In other embodiments of the present invention, the urging device **62** that provides the force for closing the template members **20, 30** can be an actuator such as an electrical, pneumatic, or hydraulic actuator. Alternatively, various other urging devices can be used to provide a force for closing the template members **20, 30** including springs, other configurations of weights, magnets, and the like.

Preferably, the aperture **40** defined by the first and second template members **20, 30** corresponds to the reference size of the tubular member **14** when the template members **20, 30** are configured with a small gap **44** therebetween. The gap **44** can be defined between the first plates **24, 34** of the opposite template members **20, 30** and similarly between the second plates **26, 36** of the opposite members **20, 30**. Further, the gap **44** can be defined between the members **20, 30** on both sides of the aperture **40**, i.e., between the aperture **40** and the hinge **42** and between the aperture **40** and the measurement device **50**. Thus, if the cross-sectional size of the tubular member **14** is about equal to the size of the aperture **40**, when the tubular member **14** is provided in the aperture **40**, the template members **20, 30** can be adjusted toward the closed position to exert an urging force on the tubular member **14** in the aperture **40**. The force provided by the urging device **62** can urge the tubular member **14** to a cross-sectional shape corresponding to the shape of the aperture **40**, i.e., the reference shape of the tubular member **14**. For example, if the reference shape of the aperture **40** is a circle with a diameter of 9 inches, and the tubular member **14** has a generally circular cross-sectional shape with a diameter of about 9 inches, the tubular member **14** can be urged by the template members **20, 30** to the round shape defined by the aperture **40**. If the cross-sectional shape of the tubular member **14** is not round, e.g., defines an eccentric or oval cross-section, the template members **20, 30** can urge the tubular member **14** to the round shape of the aperture **40**.

Further, the relative position of the template members **20, 30**, when closed against the tubular member **14**, is indicative of the cross-sectional size of the tubular member **14**. That is, if the tubular member **14** has a cross-sectional size that is greater than the size of the aperture **40**, the template members **20, 30** will be closed to a lesser extent, and if the cross-sectional size of the tubular member **14** is less than the aperture **40**, the template members **20, 30** will be closed to a greater extent.

Advantageously, the gap **44** provided between the template members **20, 30** can be sufficiently large that the template members **20, 30** can be closed to decrease the size of the aperture **40** to the minimum size of the tubular members **14** that are to be measured in the apparatus **10**.

By measuring the relative position of the first and second template members **20, 30**, the cross-sectional size of the tubular member **14** in the aperture **40** can be determined. For example, the measurement device **50** can be used to determine a gap measurement that corresponds to the size of the gap **44** between the template members **20, 30**, and the gap measurement can then be used to determine the diameter of the tubular member **14**. The correlation between the gap measurement and the diameter of the tubular member **14** generally depends on the structure and configuration of the particular apparatus **10**. For example, as illustrated in Figure 1, the measurement device **50** is configured to measure the relative position of the template members **20, 30** at a position opposite the aperture **40** from the hinge **42**, though the measurement device **50** can alternatively be configured at other positions.

According to one embodiment of the illustrated configuration, an empirical correlation between the gap measurement and the diameter of the tubular member **14** was determined to be as follows:

$$\text{Diameter of tubular member} = \frac{X}{\pi}\left(\frac{2.3+D}{15.6}\right)+D$$

where X is the gap measurement of the measurement device **50** in inches and D is the diameter of the reference aperture **40**. Thus, for template members **20, 30** defining an aperture **40** with a diameter of 4.25 inches, the diameter of the tubular member **14** is equal to (4.25 + 0.134 X). Similarly, for apparatuses **10** having apertures **40** of diameters equal to 6, 9, and 12.75 inches, the diameter of the tubular members **14** measured therewith can be determined according to the following simplified equations:

6-inch diameter apertures: Diameter of tubular member = 6 + 0.169 X

9-inch diameter apertures: Diameter of tubular member = 9 + 0.231 X

12.75-inch diameter apertures: Diameter of tubular member = 12.75 + 0.307 X

The measurement device **50** can be configured to display or otherwise report the gap measurement or the particular characteristic of interest of the tubular member **14**. For example, the monitoring device **58** can include a liquid crystal display **59**, on which

the measurement device **50** can display the gap measurement, i.e., X, in linear measurement units, or the device **50** can perform the necessary mathematical calculation to determine and display the diameter of the tubular member **14**.

It is appreciated that the diameters described above are exemplary diameters corresponding to common duct sizes, but the apparatus **10** can similarly be used to measure tubular members **14** of any size, including very small members and very large members. Further, the correlations described above between the gap measurement of the measurement device **50** and the diameter of the tubular members **14** were developed for a particular apparatus **10** and will likely vary for other apparatuses, even apparatuses similar in configuration to the one described.

The apparatus **10** can be calibrated before use or between measurement operations. For example, a calibration tool **64** having a predetermined thickness can be positioned between the first and second template members **20, 30**. The calibration tool **64** is shown in dashed lines in Figure 2 for illustrative clarity. The second template member **30** can be closed with the calibration tool **64** positioned between the template members **20, 30** so that the gap **44** therebetween is equal to the thickness of the calibration tool **64**. The measurement device **50** can then be adjusted mechanically or electronically until the device **50** reports a gap measurement, diameter, or other measurement corresponding to the calibration tool **64**. For example, the calibration tool **64** can have a first portion defining a thickness corresponding to the gap between the template members **20, 30** when the aperture **40** defines the reference shape, i.e., the desired or nominal cross-sectional shape of the tubular member **14**. With the first portion of the calibration tool **64** disposed between the template members **20, 30**, the measurement device **50** can be calibrated to the measurement that corresponds to the reference diameter. Other portions of the calibration tool **64** or different calibration tools can also define other thicknesses. For example, second and third portions of the calibration tool can define thicknesses equal to the gap between the members **20, 30** that correspond to diameters of the aperture **40** that are greater and smaller than the reference diameter, e.g., 0.03 inch greater and 0.03 inch less than the reference diameter. Thus, the second and third portions of the calibration tool **64** can be used to calibrate the measurement device **50** for the corresponding diametrical measuring positions. Alternatively, calibration can be

performed by other methods, e.g., by disposing a member of known cross-sectional shape in the aperture **40** and adjusting the measurement device **50** accordingly.

In operation, the apparatus **10** is configured to urge the tubular member **14** generally to the cross-sectional shape defined by the aperture **40** and determine the diameter or other cross-sectional characteristics of the tubular member **14** with the tubular member **14** so configured. Thus, if the cross-sectional shape of the tubular member **14** does not correspond precisely to the cross-sectional reference shape of the aperture **40**, the tubular member **14** is adjusted to the reference shape before measurement. For example, if the reference shape of the aperture **40** is circular, but the tubular member **14** defines a non-round cross section such as an elliptical cross section, the apparatus **10** urges the tubular member **14** to the round cross-sectional shape and determines the diameter of the tubular member **14** when adjusted to the configuration of the reference shape.

Advantageously, the apparatus **10** can also be used to measure a tubular member **14** that defines one or more features. For example, as shown in Figures 3 and 4, the tubular member **14** defines an aperture **16**, such as is typically provided for fluidly connecting the tubular member **14** to another tubular member **14** or to an other fluid device. While the aperture would make accurate measurement of the tubular member **14** difficult or impossible using a pi tape or a coordinate measuring machine, the apparatus **10** according to the present invention can measure the diameter of the tubular member **14** proximate to or coincident with the aperture **16**, e.g., at the longitudinal position $\mathbf{D_6}$ shown in Figure 3.

Further, while the foregoing discussion describes the determination of the diameter of the tubular member **14**, it is also appreciated that other cross-sectional characteristics of the tubular member **14** can similarly be determined. For example, the measurement device **50** can be configured to determine the circumference of the tubular member **14**, the cross-sectional area of the tubular member **14**, the wall thickness and/or eccentricity of the tubular member **14**, and the like.

Figures 5, 5A, and 6 illustrate an apparatus **10** according to another embodiment of the present invention in which a plurality of measurement devices **70** are located circumferentially around the aperture **40**. The measurement devices **70** extend radially inward from one or both of the template members **20, 30** and are configured to contact the tubular member **14** when the apparatus **10** is adjusted to the

closed position. For example, the surfaces **25, 27, 35, 37** of the plates **24, 26, 34, 36** that define the aperture **40** can define tooth-like portions **68** that extend radially inward and correspond generally to the circumference of the tubular member **14**. As shown in Figure 5A, each of the tooth-like portions **68** defines a radial bore **72** extending through a respective one of the surfaces **25, 27, 35, 37**, and a measurement device **70** is disposed in each bore **72** so that a contact end **74** of the measurement device **70** is located slightly radially inward from the corresponding tooth-like portion **68**. A mounting end **76** of each measurement device **70** can be mounted in the respective bore **72**, and the mounting end **76** of each device **70** can be connected to the respective template member **20, 30**, e.g., by a threaded (screw) mount or other connection. In addition, a slot **78** or other aperture in the plates **24, 26, 34, 36** can provide access to the mounting ends **76** of the measurement devices **70**, e.g., through which connection wires **82** from each measurement device **70** can extend. The apparatus **10** can also include an electronic controller **80** that is configured to process the outputs of the measurement devices **70**. For example, the measurement devices **70** can electrically communicate with the controller **80** via the wires **82** that connect each of the measurement devices **70** to the controller **80**.

Each of the measurement devices **70** is configured to provide an output that is characteristic of a contact force between the measurement device **70** and the tubular member **14**. Each measurement device **70** can be a sensor that detects force, pressure, and/or strain and generates an electrical signal representative of the force, pressure, or strain. For example, each measurement device **70** can be a diaphragm sensor that includes a diaphragm or membrane fluidly separating a vessel of known reference pressure from a space that is open to the measured pressure. An imbalance between the measured pressure and the reference pressure deforms the diaphragm of such a sensor, and the deformation can be measured by a strain gage, an indicator needle that is mechanically coupled to the diaphragm, a linear variable differential transformer, or the like. For example, the measurement devices **70** can be miniature stainless steel diaphragm pressure sensors from Entran Devices, Inc. of Fairfield, NJ, such as those identified as models EPB-BO and EPB-CO. Various other types of sensors can also be used.

The outputs from the measurement devices **70** can be used to determine a measurement of the tubular member **14**. In particular, a variation in the wall thickness

of the tubular member **14** can be determined according to the outputs of the measurement devices **70**. For example, a variation of the wall thickness around the circumference of the tubular member **14** can affect the stiffness of the tubular member **14**. Generally, the wall of the tubular member **14** is stiffer at circumferential locations where the wall of the tubular member **14** is relatively thick, and the wall is less stiff at circumferential locations where the wall is relatively thin. Therefore, by detecting a variation in the outputs of the measurement devices **70** and, hence, the contact forces, the apparatus **10** can detect a variation in the thickness of the wall of the tubular member **14**. For example, in operation, the template members **20, 30** can be closed by providing a force **F**, as indicated in Figure 5, which can be provided by a weight, actuator, spring, or the like as discussed above.

The apparatus **10** is illustrated in Figure 7 with the tubular member **14** disposed in the aperture **40** and, in particular, with a longitudinal portion indicated by reference label $\mathbf{D_2}$ (Figure 3) disposed in the aperture **40**. For purposes of illustrative clarity, the variation in wall thickness around the circumference of the tubular member **14** is shown exaggerated in Figure 7. With the template members **20, 30** in the closed position, as shown in Figure 7, the contact ends **74** of the measurement devices **70** are located in contact with the tubular member **14**. The radial location of each of the contact ends **74** can be sufficiently radially inward so that a compressive contact force is exerted by the measurement devices **70** on the tubular member **14**, i.e., so that the tubular member **14** is at least slightly deformed by contact with the measurement devices **70**. The contact forces between the tubular member **14** and the measurement devices **70** are influenced by the stiffness of the tubular member **14**.

The outputs provided by the measurement devices **70** are referred to by reference labels $\mathbf{R_1}$-$\mathbf{R_{18}}$, as graphically illustrated in Figure 7. Figure 8 illustrates the magnitudes of the outputs $\mathbf{R_1}$-$\mathbf{R_{18}}$ according to the circumferential location of the measurement devices **70**. The controller **80** can determine an equation of a line **84** that approximates the relationship between the outputs $\mathbf{R_1}$-$\mathbf{R_{18}}$ and the circumferential location of the measurement devices **70**, e.g., using a conventional "best-fit" technique. Further, the controller **80** can use the outputs $\mathbf{R_1}$-$\mathbf{R_{18}}$ to determine a relationship that is illustrative of the thickness of the tubular member **14** at each circumferential location of the devices **70**. For example, Figure 9 illustrates the variation in wall thickness of the tubular member **14** as a function of the

circumferential locations of the measurement devices **70**, i.e., according to the outputs $\mathbf{R_1}$-$\mathbf{R_{18}}$. The controller **80** can determine the thickness of the tubular member **14** using the outputs $\mathbf{R_1}$-$\mathbf{R_{18}}$ according to a theoretically determined relationship therebetween, or using a relationship that is derived empirically. For example, an empirical relationship can be derived by correlating output values from the measurement devices **70** with wall thickness values determined by other measurement techniques such as mechanical measurement, ultrasonic measurement, and the like. The controller **80** can determine an equation of a line **86** that approximates the variation of the wall thickness around the circumference of the tubular member **70**, as shown in Figure 9.

The eccentricity of the tubular member **14** generally refers to the difference between the maximum wall thickness and the minimum wall thickness at a particular longitudinal position along the length of the tubular member **70**. The eccentricity can be measured at various longitudinal positions of the tubular member **70**. For example, the eccentricity can be determined at each of the longitudinal positions $\mathbf{D_1}$-$\mathbf{D_8}$ shown in Figure 3. Thus, the eccentricity at longitudinal position $\mathbf{D_2}$ is about 7 mm, i.e., the difference between the maximum thickness (14 mm, measured as output $\mathbf{R_9}$) and the minimum thickness (7 mm, measured as outputs $\mathbf{R_1}$ and $\mathbf{R_{18}}$). Figure 10 illustrates a variation of the eccentricity of the tubular member **70** along the longitudinal direction of the tubular member **70**. The controller **80** can determine an equation of a line **88** that approximates the variation of the eccentricity along the length of the tubular member **70**, as shown in Figure 10.

Many modifications and other embodiments of the invention will come to mind to one skilled in the art to which this invention pertains having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the invention is not to be limited to the specific embodiments disclosed and that modifications and other embodiments are intended to be included within the scope of the appended claims. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.